U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB80-130370

High Gradient Magnetic Particulate Collection

Research Triangle Inst, Research Triangle Park, NC

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, NC

1978

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. PB80-130370
EPA-600/J-78-151	JOURNAL ARTICLE	

4. TITLE AND SUBTITLE	5. REPORT DATE
High Gradient Magnetic Particulate Collection	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
D. Drehmel (IERL-RTP) and C. Gooding (Research Triangle Institute)	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Research Triangle Institute Box 12194 Research Triangle Park, NC 27709	11. CONTRACT/GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
EPA, Office of Research and Development **Industrial Environmental Research Laboratory** **Research Triangle Park, NC 27711**	Journal Publication 14. SPONSORING AGENCY CODE **EPA/600/13**

15. SUPPLEMENTARY NOTES This Journal article was presented at the 82nd National AIChE Meeting, (Atlantic City), and was published in the AIChe Symposium Series, #175, 1978 (Vol. 74)

16. ABSTRACT This paper describes the initial phases of an evaluation of high gradient magnetic separation (HGMS) as a potential method of fine particle collection from industrial stack gases. HGMS is a relatively new separation technique that has been shown to be capable of removing small, weakly magnetic particles from liquids at high process rates. The design and operation of a bench-scale apparatus is described, and preliminary experimental results are discussed. HGMS is found to be capable of high efficiency collection of submicron particulate from a stream of redispersed basic oxygen furnace dust. Preliminary projections indicate that full-scale capital costs and power requirements would be reasonable.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Dust Collectors	Stationary Sources	13A
Flue Gases	Particulate	21B
Magnetic Separators	High Gradient Magnetic Separators	13I
Basic Converters		11F
Oxygen Blown Converters		

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Release to Public	**Unclassified**	10
	20. SECURITY CLASS (This page) **Unclassified**	22. PRICE A02 - A01

EPA Form 2220-1 (9-73)

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
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EPA-600/J-78-151
JOURNAL ARTICLE

HIGH GRADIENT MAGNETIC PARTICULATE COLLECTION

AIChe Symposium Series, 74(175):157-164, 1978

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and
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High gradient magnetic separation (HGMS) is a relatively new separation technique that has been shown to be capable of removing small, weakly magnetic particles from liquids at high process rates. This paper describes the initial phases of an evaluation of HGMS as a potential method of fine particle collection from industrial stack gases. Liquid system applications and theoretical explanations of the process are reviewed. The design and operation of a bench-scale apparatus is described, and preliminary experimental results are discussed. HGMS is found to be capable of high efficiency collection of submicron particulate from a stream of redispersed basic oxygen furnace dust. Preliminary projections indicate that full-scale capital costs and power requirements would be reasonable.

INTRODUCTION

The information presented in this paper describes a combination of magnetic and filtration collection mechanisms intended to provide a more extensive selection of particulate control devices. Besides such currently available options as scrubbers, fabric filters, and electrostatic precipitators, there is now, with its strong potential for economical application, a significant new technology called magnetic filtration or, more descriptively, high gradient magnetic separation (HGMS).

Recently purification of various types of wastewater using high gradient magnetic separation has been demonstrated (1). Conventional magnetic separation devices are generally useful for the separation of relatively large particles of strongly magnetic materials such as iron and magnetite. HGMS, by contrast, makes possible the efficient separation of micron-size particles of weakly paramagnetic materials from liquids at high process rates. It can be shown through generalized theory that application can also be made to particle removal from gas streams. Magnetic forces can be cost effective if the control device is properly designed.

Environmental Protection Agency, IERL/RTP and Research Triangle Institute, Durham, N. C.

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In its simplest practical form, the high gradient magnetic separator consists of a canister packed with the fibers of a ferromagnetic material (such as a stainless steel wool) and magnetized by a strong external magnetic field (Fig. 1). The strong magnetic forces produced near the edges of the fibers are capable of trapping fine, weakly magnetic particles with high efficiency.

The packing density of the separation zone can be adjusted to obtain a proper balance between conventional filtration phenomena and the HGMS effect. Reducing the packing density lowers the pressure drop through the separator but requires a higher magnetic field for efficient particle collection. The overall particle collection efficiency is theoretically a function of the applied magnetic field, of filter mesh parameters (fiber diameter and magnetization, packing density, and length of mesh in the direction of flow), of particle parameters (magnetic susceptibility and diameter) and of fluid parameters (superficial velocity and viscosity).

High gradient magnetic separation has been applied extensively to particle/liquid separations (1,2,3,4). The primary commercial application has been in the removal of weakly magnetic color bodies less than 2 μm in diameter from kaolin clay. Pilot-scale and

laboratory tests have been conducted on industrial waste process water from steel mills and electroplating operations, on nuclear reactor coolants, and on oils and hydraulic fluids (to remove wear particles). Preliminary experimentation shows promise of application of HGMS to the desulfurization of coal and to the reduction of solids and dissolved orthophosphate from municipal waste. The latter application is preceded by seeding of the waste stream with a magnetic material that becomes chemically or physically associated with the pollutant. Another recent novel experimental application is to the separation of red cells from whole blood.

Commercial-scale HGMS devices have been built for cyclic operation (i.e., a stationary mesh which is periodically removed from service for cleaning) as well as for continuous operation. In the continuous units, the mesh is packed into an annular ring. The ring is continuously rotated through the magnetic field zone where paramagnetic particles are removed from the fluid stream. After passing through the separation zone, each segment of the mesh rotates through a zero-field flush zone for removal of the collected particles.

The bench-scale experimental work described in this paper was the first known attempt to apply HGMS to particle/gas separations. The primary area of application interest is stack-gas cleanup in the iron and steel and ferroalloy industries. Semiempirical extrapolation of results from particle/ liquid separations indicates that in these industries HGMS may be a feasible, economic alternative to conventional filtration, wet scrubbing, and electrostatic precipitation.

THEORY OF APPLICATION

The collection of submicron aerosols by means of high gradient magnetic filtration requires that the magnetic force be larger than competing forces. In general, the magnetic force F_m is given by

$$\vec{F}_m = \nabla \int \vec{M} \cdot \vec{H} \; dV \qquad (1)$$

where $\vec{M}$ is the magnetization,
$\vec{H}$ is the magnetic field intensity, and
$d\vec{V}$ is the differential volume element of the aerosol.

Where the magnetization of the continuous phase is small, Equation (1) may be simplified for one dimension to

$$F_x = \int M \frac{dB}{dx} \; dV \qquad (2)$$

where B is the magnetic induction.

In accordance with the analysis of Oberteuffer (3) we may replace Equation (2) with the approximation

$$F_x = V M \frac{dB}{dx} \qquad (3)$$

where V is the particle volume.

At this point in the development it is necessary to consider a specific case as shown in Fig. 2 (3,5). A ferromagnetic wire of radius a concentrates the magnetic induction, B, so that, at a point P near the wire, the local magnetic induction is increased by the magnetization, M, characteristic of the ferromagnetic wire. At a point P', a distance ℓ from the wire, the local magnetic induction corresponds closely to that of the applied uniform field. Regardless of wire size, ℓ is on the order of a, and the field gradient due to the ferromagnetic wire is approximately M/a. For this configuration it may be shown that the magnetic force on the particle is

$$F_m = -\frac{8}{3} \pi R^3 \chi_p \left(H_o + H_o \frac{a^2}{r^2}\right) B_o \frac{a^2}{r^3} \qquad (4)$$

where R = is the radius of the particle,

χ_p = is the magnetic susceptibility of the particle, and

r = is the radial distance from the center of the wire to the center of the particle.

If magnetic force is plotted versus the ratio of wire radius to particle radius, one observes a maximum in the force at approximately 3. In other words, the magnetic force is greatest when the wire and particle radii are the same order of magnitude or, more specifically, when the wire is 3 times larger in radius than the particle. Intuitively, this conclusion may be reached in the following manner. In the free-stream uniform field the magnetic force is zero. The maximum magnetic force exists for those particles whose size corresponds to the dimension over which the average dH/dx is maximized. This condition occurs for

particles whose radius is of the same order of magnitude as the radius of the concentrating wires as pictured in Fig. 2 and is called a matched gradient system.

The primary force opposing particle capture is the hydrodynamic drag force exerted on the particle as it moves "across the current" through the fluid or when it is held in a stationary position on the wire. Stokes' law expresses this force as

$$F_D = 6 \pi \mu R v \qquad (5)$$

where F_D = hydrodynamic drag force,

μ = fluid viscosity,

R = particle radius, and

v = particle velocity relative to fluid.

Since the drag force is a function of particle radius to the first power and magnetic force is a function of particle radius to the third power, the drag force will decrease less rapidly than the magnetic force as particle size decreases. This means that the magnetic force will be dominant above some size and the drag force will dominate below that size. For iron particles in slurry this size is less than 0.01 μm for a matched gradient system (3).

In order to predict the particulate collection efficiency of a magnetic filter, it is necessary to hypothesize the controlling mechanisms. If the particles are already collected and the penetration is attributed to the loss of the collected particles, the magnetic force will retain the particles and decrease penetration and the drag force will strip off the particles and increase penetration. Penetration will be related to the ratio of magnetic to drag force. Using Equations (4) and (5) and simplification, this ratio is

$$\frac{F_m}{F_D} = \frac{-4R^2 \chi_p \left(H_o + H_o \frac{\alpha^2}{r^2}\right) B_o \frac{\alpha^2}{r^3}}{9 \mu v} \qquad (6)$$

where r is the radial distance as in Equation (4) and R is the radius of the particle. For the case where the wire radius α is much greater than the particle radius, the radial distance r will be approximately equal to α and we have

$$\frac{F_m}{F_D} = \frac{-8 R^2 \chi_p H_o B_o}{9 \alpha \mu v} \qquad (7)$$

This result may be compared to the analysis of Watson (6) where the controlling collection parameter R_c is given by

$$R_c \approx \frac{1}{2}\left(\frac{V_m}{V_o}\right) = \frac{\chi M_s H_o R^2}{9 \mu \alpha V_o} \qquad (8)$$

where R is the radius of the particle, M_s is the saturation magnetization of the wire, V_m is the "magnetic velocity," and V_o is the free-stream velocity. This approach removes the assumption that the particle is already collected and instead asserts that particles approaching the wire within a critical radial distance from the wire will be readily collected. The parameter R_c is the normalized radial distance from the wire within which the particle will be captured. The fractional penetration through a high gradient magnetic filter is consequently calculated by the following expression derived from the development according to Watson.

$$P = \frac{N_{out}}{N_{in}} = \exp\left(-\frac{4FR_cL}{3\pi\alpha}\right) \qquad (9)$$

where P is the fraction of particles penetrating the filter,

N is the number of particles,

F is the volume density of the filter (or 1 minus the void volume), and

L is the length of the filter in the direction of fluid flow.

SCOPE OF EXPERIMENTAL WORK

The experimental test program was planned to evaluate on bench-scale equipment the preliminary economic and technical feasibility of high gradient magnetic separation for fine particle collection. Conventional fine particulate control methods in the air pollution field are generally characterized by a limited range of capital costs and energy requirements. Although the actual values vary greatly with the specific technology and application, many installations fall within rule-of-thumb ranges of about $1 to $4/(cu.ft./min.) for uninstalled primary equipment cost and 1 to 2 h.p./(1000 cu.ft./min.) for power consumption. Unless high gradient magnetic separation demonstrates satisfactory performance with reasonable estimated capital cost and power requirements or exhibits some other strong

advantage over present technology, it will not be viable as an alternative method of control. We, therefore, conducted experiments within a limited range of operating parameters in order to evaluate practical performance.

Major power requirements of HGMS in a particle/gas system are generation of the magnetic field and operation of gas-moving equipment. By calculation one can show that a magnetic field of more than a few kilogauss requires excessive power and capital expense; therefore it cannot be attractive. Even with a low field, blower energy requirements are sufficient to limit the practical pressure drop through the filter mesh and ductwork to a few inches of water. Pressure drop through the separator is a function of superficial gas velocity, mesh void volume, and mesh length. Preliminary estimates show that gas velocities of about 1000 ft./min. or higher will be required to lower equipment size (i.e., capital cost) to acceptable limits and to provide a competitive power-to-throughput ratio.

The experimental objectives of this study were therefore to characterize performance of HGMS in a particle/gas system with the following approximate constraints:

(1) magnetic field < 10 kilogauss.

(2) pressure drop < 10 in. H_2O.

(3) velocity > 1000 ft./min.

Comparison of experimental results with the theoretical models discussed above was also a desired objective.

APPARATUS

The experimental apparatus utilized in these studies is shown schematically in Fig. 3. Basically, the apparatus consisted of a fluidized-bed system to redisperse the dust, followed by a section in which the dust was diluted with clean air. The dirty air stream was then passed through the magnetic separator and vented. Samples were extracted upstream and downstream of the magnetic separator and analyzed to determine the particle size distribution and concentration.

A dust-redispersing system was chosen for source simulation because it allowed the use of an actual industrial dust and a relatively large feed rate in comparison with the product and feed rate of artificial particle generators. The fluidized-bed system was similar in principle, although somewhat different in application, to equipment described by Guichard (7), Moreno and Blann (8), and Willeke et al. (9) The fluidized medium was nickel metal powder sieved to a size range of approximately 75 to 100 μm. Fluidizing air was compressed and cooled, run through an entrainment separator and submicron filter, and metered into the bed to provide a superficial velocity of approximately 15 cm/sec.

The test dust was selected as a likely candidate for application of HGMS. It was obtained from the hoppers of an electrostatic precipitator which controls emissions from a basic oxygen furnace (BOF) at a Pennsylvania steel mill. This type of dust is typically 90% ferric oxide (Fe_2O_3). The dust was fed into the fluidized bed by a small screw feeder. The fluidized nickel spheres deagglomerated the bulk dust, allowing it to be entrained in the superficial air flow. At the 15 cm/sec. superficial velocity, the maximum BOF particle size entrained was approximately 40 μm. The density difference in the nickel spheres and BOF dust was sufficient to ensure that none of the nickel spheres were elutriated. In the initial experiments BOF dust accumulated in the bed until a steady-state bed depth was obtained. For the remainder of the experiments, the bed consisted of approximately 50% nickel spheres and 50% BOF dust by volume.

The fluidized-bed technique of redispersing industrial dust is intriguing in itself, and no completely satisfactory quantitative description of the process has been developed. Unfortunately, a detailed study of the fluid-bed dynamics and aerosol generation was beyond the scope of the current investigation. For our purposes, the fluidized bed did provide a reasonably consistent flow of primarily deagglomerated particles.

The fluidized BOF dust was diluted by mixing with a stream of clean room air. The incoming air was preheated to 100°F to reduce the relative humidity and filtered to remove some of the background particulate. The dirty air stream was then fed to the high gradient magnetic separator, which consisted of a 3.5-in.-diameter by 8 in.-long plug of steel wool loosely packed in a steel canister and placed in the bore of a solenoid. The applied magnetic field could be adjusted in 6 increments from 0.94 to 9.65 kilogauss. The clean air stream leaving the separator was metered for flow and vented.

Sampling and analysis were accomplished using a custom-made dilution system and a commercial optical particle analyzer. Sequential sampling was conducted upstream and downstream of the HGMS apparatus to determine the collection efficiency as a function of particle size. Since rather long extractive sample lines were required, information on the larger particles (3 μm and above) was unavoidably lost, but the capture efficiency of these larger particles was qualitatively deduced as explained in the following section.

Dilution of the samples was required to avoid coincidence loss in the optical analyzer. Specifications for the dilution system were obtained through the courtesy of Southern Research Institute in Birmingham, Alabama. In the SRI-designed diluter the sample stream was fed into a conical vessel where it was mixed in highly turbulent flow with a clean stream of dilution air. A dilution ratio of 50:1 was used. This type of diluter has been shown to yield representative samples at the predicted dilution ratio for particles under 2 μm in diameter.

The particle analyzer was a Climet Model 208A, which uses near forward scattering of visible light to count and size particles in discrete increments down to 0.3 μm in diameter.

The optical particle analyzer was chosen primarily because it allowed the measurements to be made in near real time, in comparison with widely used inertial impactors, which are considerably more tedious to use and can only yield results over an integrated sample time. A few samples were also collected with an Andersen impactor to get a more complete picture of the inlet particle size distribution. The total mass efficiency of the HGMS apparatus was also determined gravimetrically for selected runs by collecting upstream and downstream samples on filters.

RESULTS AND CONCLUSIONS

Total mass concentrations of BOF dust on the order of 0.01 to 0.1 g/m^3 were produced by the redispersion apparatus described above. Fig. 4 shows a representative particle size distribution at the inlet of the magnetic separator. The distribution is skewed more toward larger sizes than are typical primary emissions from a basic oxygen furnace, indicating that some of the dust was still in an agglomerated form.

With the high gas velocities and relatively high mesh void volume, the average collection efficiency with no applied magnetic field was low--typically about 50% for 1.7-μm particles and 25% for 0.5-μm particles (Figure 5). The data were somewhat scattered. Deagglomeration of larger particles upon high-velocity impaction on the mesh fibers was the suspected cause since efficiencies of less than zero were occasionally measured for the smaller particles.

The most important feature of Fig. 5 is the dramatic improvement of collection efficiency when a low-strength magnetic field was applied. These data are representative of the behavior observed in the entire series of tests run with the bench-scale collector. Velocities ranged from about 1000 ft./min. to slightly over 2000 ft./min. Mesh void volume was varied from 0.983 to 0.991, keeping the pressure drop in the range of 2 to 12 in. of water across the 8-in. length of the mesh. Higher void fractions could not be obtained without a significant loss of physical strength and consistency in the mesh. Magnetic fields of 0.94, 2.14, and 3.08 kilogauss were used. Higher fields were not needed because in all tests the collection efficiency approached detectable limits with the 3.08 kilogauss field. Although collection efficiency data could not be obtained with the extractive sampling apparatus for particles larger than 3 μm, total mass efficiencies of 99.7 to 99.9% were measured in runs similar to the 0.94-kG case shown in Fig. 5, indicating that essentially all of the larger particles were collected.

With reference to the theoretical models discussed earlier--Equations (7) and (8)--an attempt was made to compare the effects of selected parameters with predicted behavior, recognizing the limitations presented by data scatter and the relatively small ranges over which the parameters were varied. The following results were obtained.

(1) Penetration does not vary with the particle diameter squared as indicated. Diameter to the first power seems to be more nearly correct although this modification does not bring all of the data into agreement.

(2) The effect of increasing the magnetic field above the minimum experimental value of 0.94 kG was found to be less than theory predicts. However, increasing

the mesh packing density (1- void volume) resulted in a greater improvement in collection efficiency than was predicted. Both of these latter observations could be due to physical strength characteristics of the filter mesh. Application of the magnetic field was observed to deform physically the rather loosely packed meshes, particularly the less dense ones. It is possible that this deformation created more open flow channels between fibers and also caused detrimental interference between the field gradients produced by adjacent wires. These phenomena would diminish the beneficial effects of a higher field and enhance the benefits of a more dense mesh.

Development of a physically consistent model to explain these discrepancies from the existing theory has been explored, but the results are not yet satisfactory.

Despite the uncertainties in theoretical understanding, it is evident that high gradient magnetic separation offers sufficient promise of application to the collection of BOF dust to warrant further investigation. The results shown in Fig. 5 can be translated into a projected energy requirement of approximately 2 h.p./(1000 cu.ft./min.) with the 2.14-kilogauss field and indicated pressure drop. Of this total power usage, approximately 10% would be required for production of the magnetic field with the remainder supplied to a blower of 60% mechanical efficiency. Intuitively, these estimates suggest that the use of a less dense mesh (hence lower pressure drop but higher required magnetic field) might actually result in a lower total energy requirement. Preliminary estimates for a 125,000 cu.ft./min. installation corresponding to the same conditions shown in Fig. 5 result in an uninstalled cost of approximately $4/(cu.ft./min.) for the magnet, power supplies, and magnet cooling equipment.

Both the power requirement and capital cost estimates are of course very rough at the present stage of development, but they are reasonable in comparison with the figures on conventional particulate control technology. Additional experimental work will be required to reconcile the differences between experimental observations and theoretical predictions, to identify other particle/gas separation problems to which high gradient magnetic separation might be applicable, and to refine economic estimates for specific promising applications such as particulate emission control from basic oxygen furnaces.

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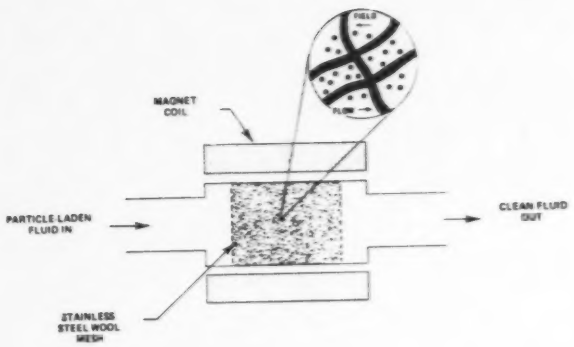

Figure 1. Schematic representation of a high gradient magnetic separator.

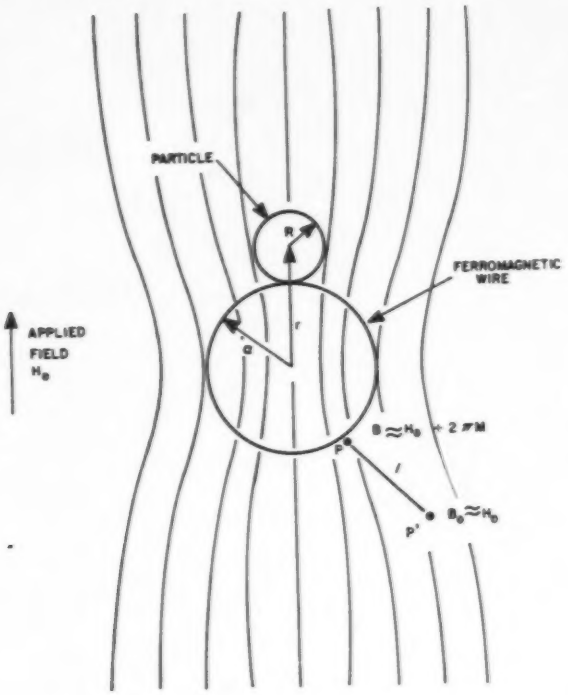

Figure 2. Cross section of a spherical paramagnetic particle captured on a cylindrical ferromagnetic wire in a homogenous applied field.

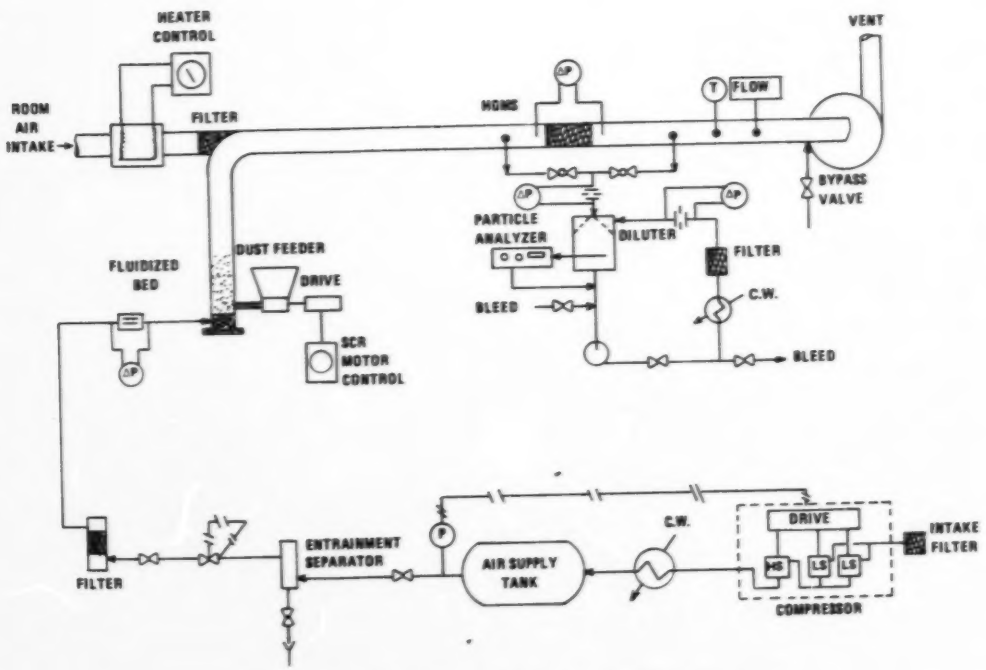

Figure 3. Bench-scale apparatus used in preliminary HGMS experiments.

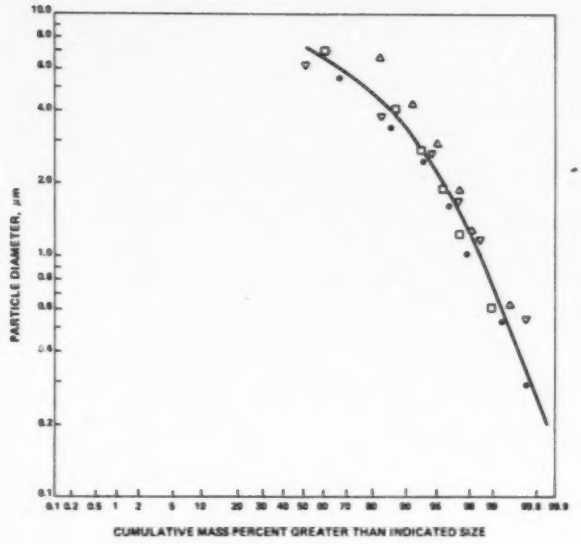

Figure 4. Size distribution of re-dispersed BOF dust.

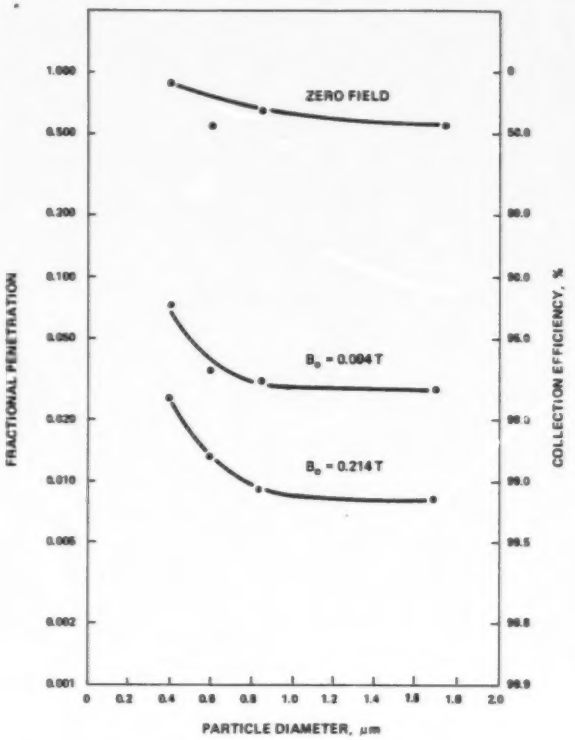

Figure 5. Experimental collection of BOF dust at a superficial gas velocity of 1660 ft/min. Mesh void fraction = 0.987 and pressure drop = 6.8 in. H_2O.